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JOINT OCCURRENCE OF HIGH TIDE AND STORM SURGE IN CALIFORNIA

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Abstract

High tides or high storm surges separately generally do not pose a hazard for flooding or structural damage in California. However, when storms and periods of high tides coincide, the potential for damage to boating infrastructure and other coastal facilities is great. This was demonstrated during the winter of 1982-1983, when extreme tides, frequent storms and additional sea level increases due to climate fluctuations related to el Nino, contributed to cause over $100 million in damage to the California coast. During January 1988 a single severe storm caused massive damage to the small craft facility at King Harbor in Redondo Beach, California. The destruction from this event could have been even more severe and far more widespread had the timing of the high tide, storm surge and large waves, been closer. In order to assess the risk of coastal flooding from their simultaneous occurrence, it is necessary to estimate the joint probability distribution of tides and storm surge. The principle conclusion of this study is that the precise coincidence of extreme tides and peak storm surge, fortunately, is exceedingly rare.

Introduction

Sea level is one of the fundamental parameters needed in the design of marinas, harbors and any other coastal improvements. Sea level information is crucial for establishing the design height of breakwaters and determining their level of protection. A great deal of concern has recently been raised about the possibility and consequences of an accelerated rise in sea level owing to global warming and enhancement of the greenhouse effect. A drastic increase over the observed rate of global sea level rise over the past 100 years, estimated at between 10 and 20 cm per century, would have serious long-term consequences for the shorelines and the coastal developments of the U.S. and the rest of the world (National Research Council, 1987 and 1990). Most reasonable scenarios, however, do not foresee drastic or catastrophic problems that can not be solved by some combination of retreat and engineering structures, depending on location.

The design water level on the California coast is determined by the combination of tide height and storm surge, with a contribution from seasonal and inter-annual changes. Seasonal changes are mainly associated with the annual cycles of heating and cooling and atmospheric pressure variation (Reid and Mantyla, 1976), with typical amplitudes of 10 to 15 cm. Inter-annual sea level signals on the west coast of North America are related to the el Nino-Southern Oscillation (ENSO) phenomenon, a large scale Pacific basin oceanographic and atmospheric perturbation (Chelton and Davis, 1980). Coastal mean sea levels can be raised as much as 15 cm for a year or more in a severe ENSO event, such as during 1982-1983 (Flick and Cayan, 1984). Severe events occur only a few times per century, but milder episodes recur on average about every 4 years (Quinn, et al., 1978).

The present paper presents preliminary results of an ongoing analysis of long records of hourly sea levels from California stations. The study goals are to examine the processes that cause high sea levels and to establish the recurrence intervals of coastal and harbor flooding.

Previous Work

Relatively little attention has been focused on the engineering aspects of U.S. coast sea level fluctuations on time scales from days to decades. In particular, virtually no studies exist that address the risk of flooding from the joint occurrence of high tides and high storm surge on the west coast of the United States (Disney, 1955; Smith and Leffler, 1980; U.S. Army Corps of Engineers, 1988; Flick and Badan-Dangon, 1989). The work that has been done generally used monthly highest total water level observation tabulations published by NOAA, and perhaps subtracted the predicted tide corresponding to the particular day of the peak. This method generally does not recover the proper surge statistics, since the results are biased by the tidal variation which dominates the total signal.

In contrast, considerable effort has gone into such studies along the coast of Britain (Pugh and Vassie, 1980; Walden, Prescott and Webber, 1981 and 1982; Pugh, 1987; Tawn, 1988; Tawn and Vassie, 1989), and to a lesser degree, the coasts of Canada and Australia (Middleton and Thompson, 1986; Hamon and Middleton, 1989; Bardsley, Mitchell and Lennon, 1990). This relatively sophisticated work has resulted in methods useful for estimating joint probability recurrence interval statistics from short sea level records by exploiting the fact that the tides are essentially deterministic and predictable. The tidal "probability" distribution can therefore be calculated exactly and combined with the measured statistics of the residual (including everything except tide) to arrive at the joint probability at a particular site.

Most recently, Coles and Tawn (1990) have extended this idea by using coastal ocean dynamics to model the *spatial* structure of the tide and the surge enabling them to derive a flooding risk assessment for the entire coast of Britain, including uninstrumented sites. Such a model is useful for evaluating the relative coastal impacts of anticipated global climate change symptoms, such as mean sea level increase and changes in storm intensity, frequency or path.

San Francisco Tide Data

None of these works has, however, examined in detail long, hourly sampled data series. Such a time series exists from San Francisco where tide gauge measurements began in 1854, forming the longest continuous record in North America. Hourly data from San Francisco starting in 1955 are routinely available from the National Ocean Service, NOAA. During the 1960's, efforts led by Professor Walter Munk at the Institute of Geophysics and Planetary Physics (IGPP) at the University of California, Scripps Institution of Oceanography, resulted in digitized hourly data from many locations, including San Francisco, starting there in 1897. Combining data from the two sources produced a time series covering 1900-1989, a total of 788,928 hours. Sea level residual was calculated by subtracting the

predicted tide from these raw digitized data values over the 90-year study period. The hourly tide prediction was made using standard NOAA tide constituents *including* seasonal changes in mean sea level.

The entire residual time series was plotted and visually examined to identify and repair the approximately 18,000 hours of gaps, glitches and amenable timing errors in the original data. Timing errors are the most common and vexing problem with tide records and can result from float-well clogging or clock drift (Agnew, 1986), as well as by displaced segments of data, sometimes days or weeks long, and commonly found adjacent to gaps. Timing problems show up as either suddenly or steadily increasing tidal frequency oscillations in the residual record that would be impossible to detect in the original time series. Gaps were repaired by linear interpolation, while large, obvious jumps, usually in multiples of 1 foot (the data are all archived in integer units of hundredths of feet), were appropriately adjusted. These tasks were done automatically on the computer. Misplaced chunks of data were shifted to their proper location by computer, using trial-and-error.

California Tides and Storm Surge

Tides in California cause ocean water level fluctuations that approach 300 cm at extremes, as shown in Figure 1, and thus are considerably larger than typical storm surges. In fact, tides on this coast represent the largest variation in sea level on any time scales shorter than those associated with the ice ages, which cause changes on the order of 100 m over 10's of thousands of years. The tide regime is classified as mixed, with the diurnal constituents about 70% as large as the semi-diurnal constituents. This results generally in two high and two low tides each day that are respectively unequal in height.

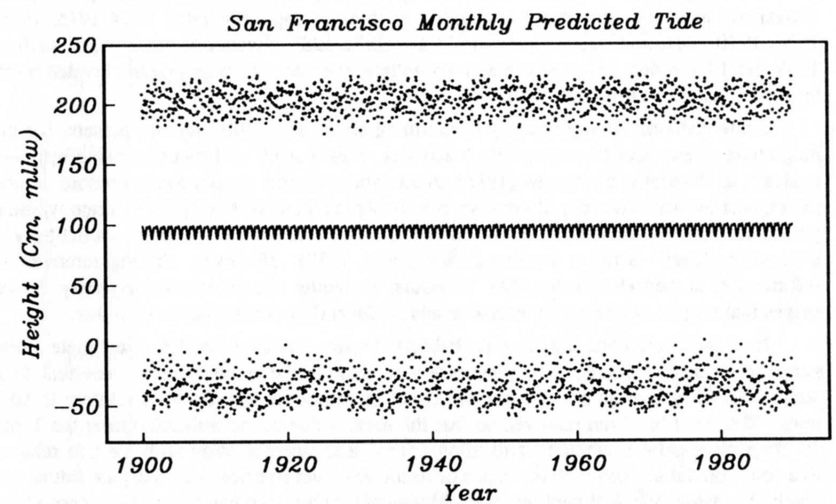

Figure 1. *Predicted monthly extreme high (upper dots), mean (solid curve) and extreme low (lower dots) tide at San Francisco over the 1900-1989 study period relative to the mean-lower-low-water (mllw) tidal datum.*

Extreme tides in California follow subtle but predictable patterns elucidated by Zetler and Flick (1985a and 1985b). The high tides reach peaks twice per month, twice per year in summer and winter, once about every 4½ years and, to a small degree, once every 18.6 years. The 4.4 year lunar perigee (half) cycle is clear in the monthly extreme high tide predictions, while the 18.6 year lunar node variation is more evident in the monthly extreme low tides, as illustrated in Figure 1. Coincidental phase relationships result in the peak monthly high tides during winter occurring in the morning, often quite early, and those in summer occurring in the afternoon or evening.

Storm surge is usually defined as that portion of the local, instantaneous sea level elevation that exceeds the predicted tide and which is attributable to the effects of low barometric pressure and high wind associated with storms. Sometimes the super-elevation of sea level due to waves and wave-induced surges is included in design calculations of storm surge, particularly for structures on beaches. As shown below, storm surges in California, *excluding the effect of waves,* only rarely approach 100 cm in amplitude, with average heights below 30 cm. The terms storm surge and sea level residual are used interchangeably in this study, although there may be a distinction based on the respective forcing functions.

Figure 2 shows the maximum, mean and minimum monthly values of sea level residual calculated over the 90-year study period. There is an obvious trend in the data corresponding to a relative sea level rise of 19.5 cm per century. The residual shows a trend since the total sea level does, while the tide predictions do not. There are also a number of prominent high sea level residual episodes with values above about 60 cm higher than the mean. During data editing procedures, these events were scrutinized since they are crucial in determining the all-important tail of the probability distribution. These highs usually correspond to years with ENSO conditions, such as during 1904-1905, 1914-1915, 1925-1926, 1940-1941, 1957-1958, 1969, 1973 and 1982-1983. Events in other years, such as 1938 and 1980 reflect severe storm activity without the added background of elevated mean levels associated on this coast with el Nino.

Some contamination, primarily from timing errors is unboubtedly still present, but the magnitude is less than 10 cm, usually much less. Future work will focus on using response analysis, as illustrated by Agnew (1986), to attempt to correct the portions of record around the highest events. The only alternative is to low-pass filter the hourly data to remove tidal period variability. Very sharp cut-off filters are available for this purpose, particularly if time series length is not a limiting factor (Pugh, 1987). However, filtering removes all information at periods shorter than 12 hours, including actual, meteorologically driven surges that may have interesting variation and peaks at time scales shorter than this.

In order to calculate unbiased probability density functions needed to estimate storm surge recurrence intervals, it was necessary to remove the trend from the residual time series. This has been done, and has the effect of raising earlier residuals relative to later ones. The trend has been removed so that the mean value of the residual during the 1960-1978 epoch remains unaltered. This allows consistent recombination with the tide relative to a common datum, and with estimates of future sea level rise trends to compute future risk levels (Bardsley, Mitchell and Lennon, 1990), although this step has not yet been carried out with the present data set. Trend removal elevates the high residual (89.3 cm) of 28 February 1941 above that of 26 January 1983 (82 cm). The 1983 event of course remains the highest *total* sea level recorded at San Francisco, owing to the near coincidence of peak high tide and a surge of about 60 cm that occurred on the morning of 27 January 1983.

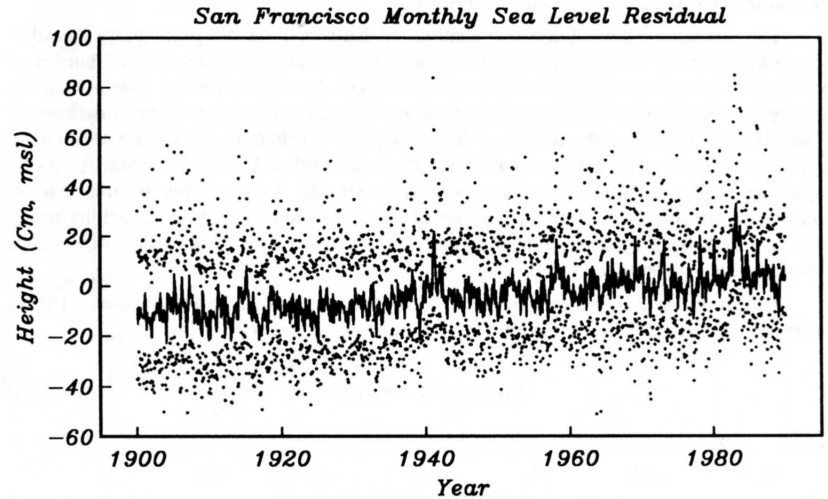

Figure 2. *Monthly extreme high (upper dots), mean (solid curve) and low (lower dots) sea level residual at San Francisco over the 1900-1989 study period relative to the mean sea level datum (msl) calculated for the 1960-1978 tidal epoch.*

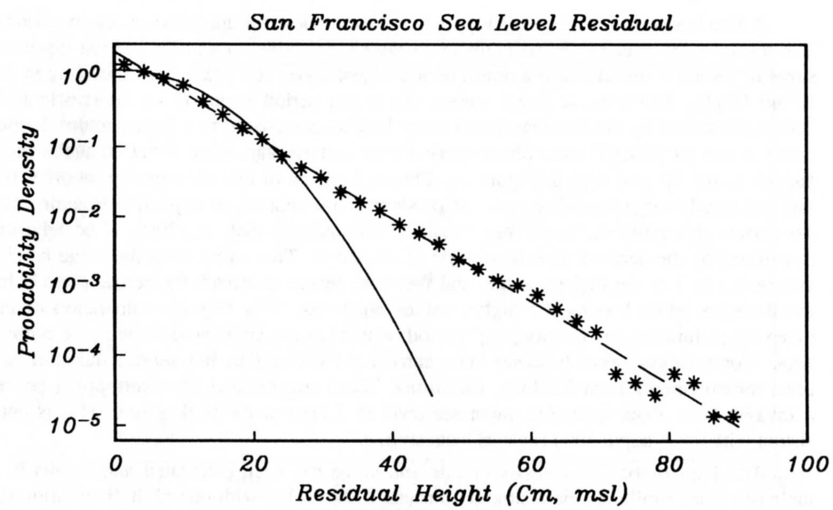

Figure 3. *Probability density distribution (stars) for positive residual sea level calculated from 90-year record of hourly data. Solid line shows Gaussian distribution, dashed line is (log) linear fit.*

Probability Distributions and Return Periods

The probability distribution for positive residuals from the 90-year hourly record is shown in Figure 3. This was calculated by simply computing the histogram, or number of occurrences of a given residual value in each bin about 3 cm (0.1 ft) wide. The probability density is then given by the histogram values normalized by the total number of data points (788,928) and the bin width. It is clear that a Gaussian distribution, shown as a solid curve, seriously underestimates the probability density in the high value tail. A linear fit to (the logarithm of) the density function does a much better job. This is important information, since Gaussian distributions are often *assumed* to fit the residual distribution (lacking strong evidence from long time series to the contrary), because of their analytical convenience (Middleton and Thompson, 1986).

The storm surge return period, T calculated from the probability distribution, $p(\eta)$ for positive sea level residuals, η according to Equation (1), is shown in Figure 4.

$$T(\eta) = [N(1 - F(\eta))]^{-1}, \tag{1}$$

where,

$$F(\eta) = \int_{-\infty}^{\eta} p(x)\, dx,$$

is the cumulative distribution function (Pugh and Vassie, 1980) and $N = 8766$ is the number of hours in a year.

A line has been fit to the data values to enable modest extrapolation of return periods. The results seem reasonable and consistent with expectations, in that the highest observed surge of about 90 cm falls near a return period of just under 100 years, corresponding to the record length. However, at lower values, the return period seems to be underestimated. This is illustrated by the fact that 60 cm surge heights correspond to a 1-year return period, when in fact they should recur about every 3 years, on average, since about 30 such events happen in the 90-year record (Figure 1). The explanation of this discrepancy involves the fact that hourly surge heights are not independent of one another, as implied in Equation (1). To correct this problem, Tawn and Vassie (1989) suggest that, in effect, N be adjusted downward by the decorrelation time scale of the surge. This varies with the surge height, decreasing to 1 at the highest surge, and therefore serves to stretch the return periods for small surges while leaving the higher values unaltered. This requires calculation of the mean surge duration, or "overtopping" period, which has not yet been done with the present data. Computations have however been carried out on similar, but shorter duration, sea level measurements from La Jolla, California. These suggest that the overtopping period decreases from about 6-days at mean sea level to 1 hour at the peak value. This is consistent with the synoptic time scale of local storms.

The joint probability density of tide and surge has been calculated and results in a table of values similar to the histogram discussed above, but with one such distribution for each bin of predicted tide height. This two-dimensional distribution matrix was summed diagonally over constant values of total tide plus residual, to yield the corresponding cumulative distribution function. The return period of total height was then calculated from Equation (1) in the same manner as before, and subject to the same constraints. The result is shown in Figure 5, where a straight line has again been fit to the data points.

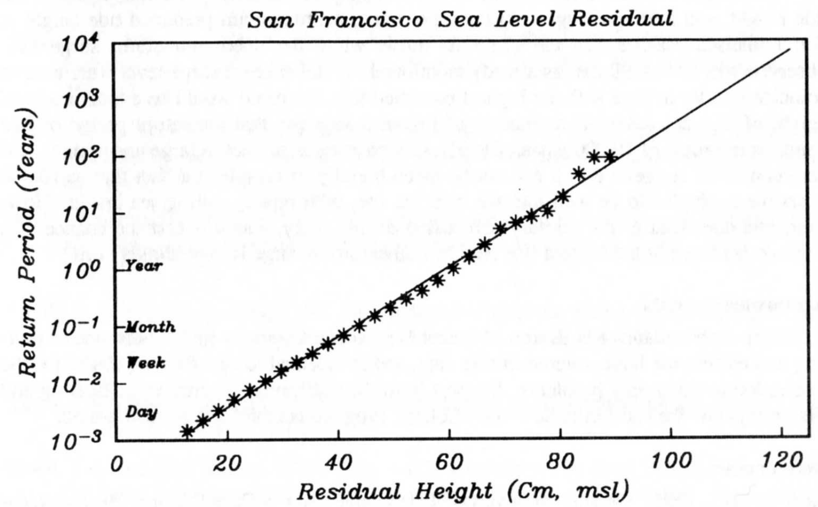

Figure 4. *Return period of sea level residual, or storm surge, calculated from the 90-year record of hourly sea level observations at San Francisco. Linear fit (solid line) is useful for modest extrapolations.*

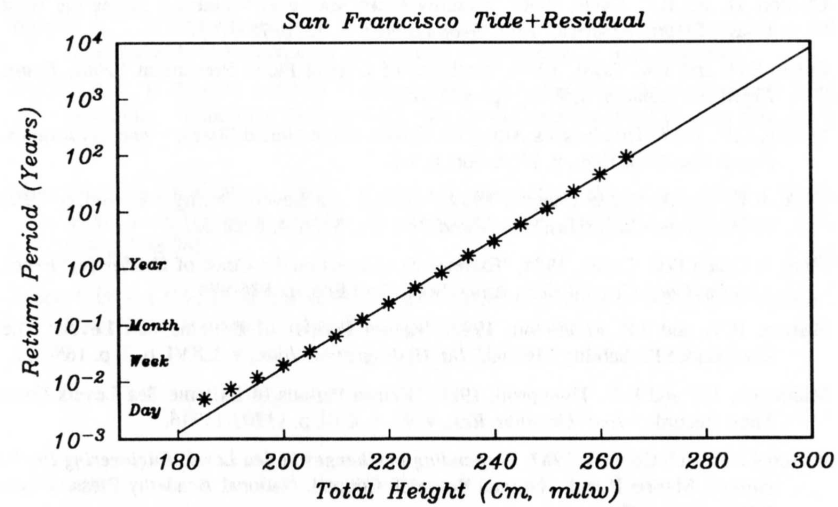

Figure 5. *Return period of total sea level height composed of tide and residual contributions calculated from the joint occurrence matrix of these variables.*

The highest total sea level observed, 265 cm above mllw, is composed of a 210 cm tide height, and a 55 cm surge. On the other hand, the maximum predicted tide height at San Francisco reaches 224 cm (7.35 ft) mllw, while the maximum storm surge ever observed was almost 90 cm, as already mentioned. If this highest surge level were ever to coincide exactly in time with the highest predicted tide, the result would be a total sea level height of 314 cm mllw. Examination of Figure 5 suggests that the return period of this height is in excess of 10,000 years. Clearly, this estimate is subject to large uncertainty, and common sense suggests that it can not be taken literally, if only for the fact that in 10,000 years the earth should be well into the next ice age, with rapidly falling sea levels. However, this does lead to the primary conclusion of this study, which is that the chance of a close coincidence of the highest tide and the highest storm surge is exceedingly slim.

Acknowledgements

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